Теорія та методика фізичного виховання
Physical Education Theory and Methodology
Teorìâ ta Metodika Fìzičnogo Vihovannâ

ISSN 1993-7989 (print)
ISSN 1993-7997 (online)
ISSN-L 1993-7989

REVIEW ARTICLE

Brain Neuromodulation Effects on Sport and Nutrition: A Narrative Review

Pierpaolo Limone[1AD], Fiorenzo Moscatelli[1AD], Alessia Scarinci[2AD], Marco Carotenuto[3BE], Antonietta Messina[3AD], Marcellino Monda[3AD], Anna Dipace[1AD], Marco La Marra[3BD], Ines Villano[1BD], Paola Bassi[3BE], Rita Polito[4BD] and Giovanni Messina[3AD]

[1]Pegaso Telematic University
[2]Mercatorum Telematic University
[3]University of Campania "Luigi Vanvitelli"
[4]University of Foggia

Authors' Contribution: A – Study design; B – Data collection; C – Statistical analysis; D – Manuscript Preparation; E – Funds Collection

Corresponding Author: Giovanni Messina, giovanni.messina@unifg.it
Accepted for Publication: February 8, 2024
Published: February 29, 2024

DOI: 10.17309/tmfv.2024.1.17

Abstract

Study purpose. At the end of the twentieth century, the development of highly reliable and painless non-invasive transcranial brain stimulation techniques and devices has aroused great scientific and clinical interest in numerous fields. In neuroscience, since the introduction of innovative and non-invasive devices such as the brain stimulator, the investigation of cortical processes and their neural basis has played a fundamental role.

Furthermore, neuroscientists are attracted to therapeutic applications for the treatment of food craving. This narrative review is aimed to explain the growing and constant interest of neuroscientific experimentation in the field of non-invasive transcranial stimulation.

Material and methods. After an introduction explaining the historical evolution of NIBS, we will try to provide an overview of the two stimulation techniques (TMS and tDCS); we will describe the different types of stimulation that can be performed using these techniques, the excitatory/inhibitory effects, and the various mechanisms of action at the level of brain activity.

Results. We will also provide some elucidations regarding the implications of the facilitative/inhibitory effects, and how these stimulation methods can be used to advance knowledge of the neurofunctional organization of the brain.

Conclusion. The results of the study showed the effect of brain neuromodulation on sports and nutrition.

Keywords: Non-Invasive Brain Stimulation (NIBS), Transcranial Magnetic Stimulation (TMS), Transcranial Direct Current Stimulation (tDCS), Cortical Excitability, food craving.

Introduction

The search for perfection in the fields of sports and nutrition is unrelenting (Forbes et al., 2022). Athletes and the teams that support them are constantly looking for new ways to improve their physical capabilities, streamline their training schedules, and sharpen their minds (Shaw et al., 2022). In the midst of this never-ending quest for top performance, the fascinating field of brain stimulation has become a potent weapon in the athlete's toolbox (Forbes et al., 2022). Brain stimulation techniques have shown the ability to revolutionize sports performance and nutrition practices, from honing cognitive skills to adjusting bodily responses. Brain stimulation refers to the use of various techniques and technologies to modulate or regulate the activity of the nervous system, particularly the brain. It involves the application of electrical, magnetic, chemical, or other forms of stimulation to specific neural pathways or regions to influence their function (Antal et al., 2022a). The brain stimulation has a wide range of applications in medicine, research, and even some emerging applications in non-medical contexts. Neuromodulation is being explored for a variety of emerging applications, including enhancing athletic performance, improving sleep quality, treating addiction, and even as a potential therapy for neurodegenerative diseases (Van Ophoven, 2023). The use of brain neuromodulation in the context of sports and nutrition involves the use of neuromodulation techniques, like transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS) to optimize brain function and enhance different aspects of athletic performance, including cognitive function, motivation, and even appetite regulation (Kesikburun, 2022). In fact, neuromodulation techniques have been explored to enhance cognitive functions such as attention, memory, and decision-making. Athletes can use these techniques to sharpen their mental acuity, which is critical for strategic planning and focus during training and competition. Moreover, considering that the brain plays a central role in regulating appetite and food intake, these techniques could be investigated for their ability to influence appetite control, potentially assisting athletes in managing their dietary choices and body weight for optimal performance. Furthermore, brain stimulation techniques have demonstrated effects on stress, cognitive improvement, motivation, mental toughness and appetite regulation, all fundamental aspects for both sport and nutrition (Barwood et al., 2016; Dumel et al., 2018; Edwards et al., 2017; Hazime et al., 2017; Lattari et al., 2018; Wang et al., 2022).

Different non-invasive brain stimulation (NIBS) techniques affect neuronal states through different means. However, the stimulation of the human brain implies, as an essential element, that these methods can induce a variation in the membrane potential of neurons. The membrane potential is an electrical voltage, measurable in a difference between the inside and the outside of the neuron (Amassian et al., 1990). This difference is given by an imbalance of positive and negative electric charged with ions. In resting conditions, the membrane potential of a neuron remains stable, thanks to a precise distribution of ions between its interior and exterior (Matsumoto et al., 2013). However, neurons are dynamic entities, capable of undergoing substantial transient variations of the membrane potential which are the basis of the transmission of information, in particular through the generation of signals which take the name of action potentials (Groppa et al., 2012). The different brain stimulation methods can modify the state of the neuron through electric currents and, consequently, favor the generation or otherwise of action potentials (Vidal-Dourado et al., 2014). TMS is mainly a neurostimulation method which involves the induction of a depolarization of the neuronal membranes and the initiation of action potentials in the stimulated area by means of an electromagnetic induction (Woods et al., 2016). The tES is neuromodulation technique that through low-intensity electrical stimulation, induces a variation in the state of the membrane potential, altering the ionic fluxes. This alteration can be a hyperpolarization or a depolarization of the neuron (Simonsmeier et al., 2018). The tES does not involve the direct induction of action potentials, but a variation of the response threshold of the stimulated neurons, with a consequent modulation of the response that the neuron will be able to provide.

Materials and methods

This narrative review tries to explain the brain neuromodulation effects on sport and nutrition. After an introduction explaining the historical evolution of NIBS, the present work tries to provide an overview of the two stimulation techniques (TMS and tDCS); describe the different types of stimulation that can be performed with these techniques, the excitatory/inhibitory effects and the various mechanisms of action at the level of brain activity. This work will also provide some elucidations regarding the implications of the facilitative/inhibitory effects, and how through these stimulation methods the knowledge of the neurofunctional organization of the brain can be broadened. Finally, it will explain the role of brain stimulation in physical exercise and nutrition. The bibliographic search was carried out on Pubmed using the following keywords: Non Invasive Brain Stimulation (NIBS), Transcranial Magnetic Stimulation (TMS), Transcranial Direct Current Stimulation (tDCS), Cortical Excitability, food craving, sport, nutrition.

Results

TMS

TMS is a non-invasive technique that allows to stimulate/inhibit or further modulate neural activity of cerebral cortex without solution of continuity. Its technical characteristics make it an important and promising tool for analyzing higher cognitive functions and the central motor pathway, making it possible to explore excitability, motor conduction and central motor conduction time. From the outset, the main source of interest in this technique has been the possibility of assessing the functionality of the corticospinal pathway in healthy subjects or subjects with neurological deficits in the motor sphere (Wagner et al., 2007). In this way, the propagation properties of the corticospinal fibers that control the target muscle can be examined in detail and the cortical representation of these muscles can be mapped, making TMS an effective technique for studying brain plasticity. Experiments show that an electric current flowing in a straight conductor generates a magnetic field around itself: it follows that a change in the magnetic field can in turn generate an induced current (Fregni & Pascual-Leone, 2007). As far as magnetic phenomena are concerned, we can consider a magnet made up of two indivisible poles. This means that there are no positive or negative magnetic charges, and the very concept of magnetic pole is fictitious: magnetic forces are a manifestation of the motion of electric charges. The properties of a magnet do not depend on the presence of "magnetic charges" inside it but on the fact that it is traversed by electric currents. There are profound links between electrical and magnetic phenomena: the study of the reactions between these is the object of electromagnetism. Let us now consider a solenoid, formed by a wire wound in a cylindrical helix and traversed by an electric current. It creates output lines which are called magnetic flux (Rossi et al., 2021a). Inside the solenoid, in the central region, the flux lines are parallel to the axis equidistant, and the magnetic field is uniform. Outside, however, the intensity is lower, the lines of flow are divergent, and the field is not uniform since the flow, going out, branches out by reducing its intensity with an index inversely proportional to the square of the distance. The magnetic flux is measured in weber (Wb) while induction, which expresses the distribution of the lines of force in space, is expressed in the head which corresponds to weber/metre^2.

In summary, an electric current can generate a magnetic field and at the same time a variation of the magnetic field can generate an induced current. By applying these observations to the neurophysiological field, it can be understood that a rapid variation of a magnetic field applied to an area of the human body a real induced current originates in its, and therefore it causes a stimulation. This observation is underpinning the development of magnetic stimulation. The magnetic impulse comes generated by the passage of current in the coil. This pulse induces a current in an electrically conductive area, such as the human body. If the current has sufficient amplitude and duration, it is possible to stimulate the neuromuscular tissues in the same way as more conventional electrical stimulation (George et al., 2002). The safety level is today guaranteed because the TMS device has a capacitor which loads and unloads (Rossi et al., 2021b). Using the charger circuit, the energy stored in the capacitor is discharged to one level pre-determined in the front control panel up to a maximum of 2.8 kV. When the stimulator receives a trigger signal as input, the energy stored in the capacitor is discharged into the stimulator coil (Zhang et al., 2022). In a few milliseconds the discharge switch can develop large currents. The switch is constructed in such a way to conduct the current in a precise direction and therefore the stimulator produces a monophasic current discharge with no reverse current. The possibility of reducing heat dispersion in the coil is linked to the monophasic discharge. The coil consists of a flat circular coil in which a variable current flow capable of produce a magnetic field (de Goede et al., 2018). Over the years, different application of TMS have been proposed and tested: single-pulse (spTMS), paired-pulse (ppTMS), repetitive (rTMS) and pattern stimulations such as theta bursts (Rossini et al., 2015). The first devices capable of delivering only a single impulse found wide use in the clinical field in the evaluation of specific neurophysiological parameters: for example, the inducible response in a peripheral muscle after having detected the primary motor cortex (M1), in order to evaluate the clinical status of the pathway which, from the cortex, carries the signal to the peripheral muscles, generating the motor evoked potential (MEP) (Moscatelli et al., 2017; Jameson, 2023). In the experimental investigations, single pulse stimulations immediately found wide use in the field of neuroscience, to evaluate the role of a brain area in a specific function of interest. The first technological developments in the field of TMS led to the development of protocols which envisaged the use of ppTMS. These protocols provided for a conditioned stimulus (CS) followed by a test stimulus (TS), allow us to evaluate how two areas are connected to each other, through the induction of cortical facilitation or inhibition phenomena. In particular, they evaluate how MEP amplitudes can be modified on the basis of the interstimulus interval between CS and TS or on the basis of the subject's status (Rossi et al., 2001; Veniero et al., 2012). In numerous protocols, the experiment involves the use of a range of intensities of the CS to induce inhibition or facilitation (starting from values below the threshold, up to values above the threshold). The intensity of the TS is usually set at 110-120% of the central motor threshold. When the two stimuli are administered in two different areas, these protocols provide important information on the degree of connection between the two areas (i.e. cortical connectivity). At the beginning of the 90s, devices capable of administering different stimuli (defined trains of stimuli) in rapid succession (rTMS) were introduced, which allowed the use of this method also in other research area. If applied as a single pulse, the induced current has sufficient amplitude to depolarize neurons (neurostimulation). If applied repeatedly at various frequencies and for a few minutes, rTMS modulates cortical excitability, decreasing or increasing it. The modulatory effect of rTMS lasts longer than the stimulation period, generally at least as long as half of the stimulation period. Much of the research investigating the effects of rTMS on cortical activity has focused on the effects of motor area stimulation, as the excitability of this brain region can be easily measured with MEPs (Moscatelli et al., 2020; Moscatelli et al., 2016). There is a large consensus in the literature that the application of low-frequency (LF) rTMS trains, below 1 Hz, induces mainly inhibitory effects, while high-frequency (HF) stimulations, above 5Hz and up to 25 Hz, induce facilitative effects (Moscatelli et al., 2023). TMS follows the rules of logical inference: if cortical area "A" is involved in cognitive process "X", and is not involved in process "Y", the alteration of the activity of area "A" will lead to an impaired performance in "X" and not in "Y" (Antal et al., 2022b). By deductive reasoning, area "A" plays a causal role in process "X" (Bortoletto et al., 2021). The functional impact of TMS essentially depends on its ability to transiently influence neuronal activity, modifying information processing, based on the state of the stimulated area. The TMS offers the advantage of indicating, along a time continuum, when a specific cognitive event occurs. In this case, the stimulation method is spTMS, because it exploits the high temporal resolution of the magnetic pulse, which is in the order of milliseconds (Lefaucheur et al., 2020). These methods are useful not only to limit the temporal activation field of a given brain area, but also to highlight the different role that the airways play in the different moments of sensory and cognitive processing (Jannati et al., 2023). However, rTMS protocols also offer the possibility of defining precise time windows. Initially, the stimulation can be applied over a large time interval (about 500 ms), just to see if it is possible to interact with the execution of the task by stimulating a given area (Lefaucheur et al., 2014). Once the involvement of this area has been established in a given time window, it is possible to reduce the stimulation time by increasingly narrowing the window (Perinelli et al., 2019). Therefore TMS, applied according to specific experimental paradigms which mainly aim at identifying the moment in which an area comes into play in a cognitive process, can identify circumscribed temporal windows of information processing. In this case, it should be noted that the effects induced by spTMS, but also by on-line rTMS, are generally short-lived, i.e., approximately a few hundred milliseconds. The case of the long-term neuromodulation effects of rTMS applied in protocols defined off-line, i.e., before the execution of the task, or those resulting from the repeated application of rTMS is different. In the online application, the longer the stimulation period and the higher the rTMS frequency, the greater the interference on the activity of the stimulated brain region and the final effects, observable in the subject's behaviors (Savino et al., 2023). However, there is an increased risk of inducing non-specific behavioral effects, which can make the results more difficult to interpret. In these cases, the use of a TMS called sham, or ineffective/

placebo stimulation, is used. During sham stimulation a TMS is simulated, but no magnetic field reaches the underlying cortex. The simplest way is to interpose a non-conductive material 3 cm thick between the coil and the scalp, alternatively you can rotate the coil by 180° (Rossi et al., 2021b). As there are multiple brain regions that may be involved in exercise regulation, the rationale for using brain stimulation for performance enhancement and the regulation of food intake, may vary accordingly, which may provide an explanation for the inconsistent results of different studies (Machado et al., 2019). It seemed that different stimulation conditions and parameters may contribute to different results (Bastani & Jaberzadeh, 2012). Moreover, warm up or training exercises conducted simultaneously with NIBS have been adopted in a few previous studies, which may be a factor to influence the results (Park et al., 2019).

rTMS

The rTMS is defined as the application of a train of pulses of the same intensity to a single brain area at a given frequency and intensity. In general, high frequency stimulation, is correlated to interference with cortical functions during the application of the pulse train. However, following these immediate effects, a train of rTMS pulses can also induce sustained modulation of cortical excitability which can persist well beyond the duration of the train itself (Amanda S Morrison, Andero Uusberg, 2022). The modulation effect can range from inhibition to facilitation based on the stimulation parameters used, as was the case for ppTMS. Lower frequencies, for example 1 Hz, applied to the motor cortex can repress its excitability, while stimulation trains at higher frequencies, around 20 Hz, they lead to an increase of cortical excitability. These effects vary depending on of the individual considered and the shape of the trains, however in general the low frequencies (around 1 Hz) produce very long-lasting and robust effects and can therefore be applied to the motor cortex and other cortical regions to study the behavioral relationships of the brain (Gornerova et al., 2023). To obtain an even more persistent and important effect in the neuromodulation of the chosen area, various stimulation frequencies are usually combined. It should be emphasized for regarding the limits mentioned above, that they are not entirely arbitrary. It is in fact known, for example, that low frequencies around 1Hz can be correlated to depression or long-term potentiation following tetanic nerve stimulation: there is evidence that demonstrates that rTMS at high and low frequencies identified above produce relatively distinct both on direct measures of brain activity and behavior. Using rTMS therefore, frequency appears to be the key parameter determining the direction of effects, although other variables should be taken into consideration while planning an experiment with this method. For example, attention should be paid to the pulse train duration, the interval between two trains, the total number of trains and pulses in a session duration or over a given area. By respecting the parameters, two main ways of performing rTMS are defined: online and offline.

Transcranial Direct Current Stimulation (tDCS)

Transcranial Direct Current Stimulation (tDCS) is a non-invasive brain stimulation method able to induce functional changes in the cerebral cortex. The tDCS essentially consists in the application on the scalp of electrodes delivering a direct current of low intensity able to crossing the scalp and influencing neuronal functions, finding application in numerous clinical, diagnostic and research fields (Cabral et al., 2015; Lattari et al., 2016, 2020). If the study of the brain has always aroused great fascination in scientists since ancient times, the effects of the current on it have been objects of large scientific and non-scientific interest since its discovery in the world. In fact, the effects of uncontrolled brain stimulation have been reported since the past. Looking at the most recent history, the use of the therapy electroconvulsive and psychiatric drugs and the lack of reliable neurophysiological signals, obscured the use of direct current on the central nervous system as a therapeutic and research tool, especially in the field of psychiatry. However, galvanic current continued to be used without interruption in the treatment of musculoskeletal disorders and peripheral pain in the meantime. These first efforts in the neurophysiological field, therefore, were probably abandoned due to lack of reliable evaluation methods. When in 1998 it was possible to measure the effects of direct current application on the motor cortex non-invasively by means of transcranial magnetic stimulation, tDCS became reliable in terms of parameters such as stimulation intensity, duration and validation of its following plastic effects (Al-Tawarah et al., 2022).

From a technological point of view, the tDCS instrumentation has a rather simple structure compared to other stimulation devices. In fact, it is mainly composed of two electrodes and a battery device capable of supplying a constant flow of current in a continuous manner. These basic components can be connected to other components, such as for example a software that offers the opportunity to choosing between different stimulation protocol or multiple-session experiments. Naturally, since they must create a closed circuit once in operation, the two electrodes correspond to a cathode and an anode. By placing them over the scalp, it can be modulating a specific area of the central nervous system. The positioning of the electrodes therefore assumes a crucial role and is usually determined in line with the international system of EEG 10-20. For example, studies exploring the motor cortex place electrodes above zone C3 and C4. The electrodes used are usually sponge and the surfaces range from 25 to 35 square, but they can change in order of size. To create the homogeneous electric field responsible for the plastic effects of the neural tissue, and therefore necessary for tissue analysis, a direct current is usually made to flow inside the electrodes which can vary from 0.5 to 2 mA, for about 20-40 minutes. It can induce even lasting changes in the brain, both excitatory and inhibitory, while remaining subthreshold. This neuromodulation technique consequently provides a practical and less invasive alternative to, for example, direct stimulation. In fact, tDCS can be used in general to manipulate brain excitability by means of polarization membrane: a cathodal stimulation hyperpolarizes, an anodal stimulation depolarizes the resting membrane potential. In this regard, it should be specified that the current flow in question is a flow of ions present in the brain tissue. Therefore, the positive ions will tend to flow towards the cathode, while the negative ones will flow towards the anode. The flow comes conventionally considered directed from the anode towards the cathode, creating as mentioned a closed circuit in which the current passes through the head. There are two main types of assembly for electrodes, but different nomenclature to define them. Therefore, for the sake of clarity, it is now necessary to discuss some terms used to describe the assembly of tDCS. When an electrode is placed under the neck, the entire assembly is referred to as "unipolar". Conversely, montages with the two electrodes on the head are usually referred to as "bipolar". This nomenclature, however, could be considered technically inaccurate, since DC stimulation is always generated by means of two poles (electrodes) which generate an electric dipole between the two electrodes. Therefore, an alternative nomenclature to use could be that of "monoencephalic" and "biencephalic" to differentiate the "unipolar" and "bipolar" set ups respectively. Researchers in the field also use the terms "reference" and "stimulation" electrode to refer to the electrode respectively neutral and active with respect to the area to be investigated. However, even the term "reference" can be problematic especially for the biencephalic montage because the reference electrode is not physiologically inert and can contribute to the modulation of activity as the active one (Woods et al., 2016). This could be a potential confounding factor. Nevertheless, the researchers use this term to underline that, in their studies, they assume that in their assembly one electrode will be considered for stimulation, while the other as reference.

Sport and brain stimulation

The brain stimulation is thought to have ergogenic potential for increasing muscular strength and stamina in both athletes and non-athletes (Goodall et al., 2014; Lattari et al., 2020; Moscatelli et al., 2023). The left dorsolateral prefrontal cortex (DLPFC) is the region that is most frequently targeted in studies of NIBS and sport because it controls the inhibition of motor regions. In general, this region plays a part in the modulation of many different processes and functions, including emotion, mood, and memory. Consequently, it is challenging to gauge the effect of a specific stimulus on just one metric (Karlinsky et al., 2017). One of the most crucial areas in determining whether or not to continue exercising is the left DLPFC since it controls exertion and weariness (Monda, Salerno, et al., 2017a). Physical exhaustion is a complicated process that may be influenced by elements like cerebral inhibition and perceived effort. EEG measurements of brain activity (beta power) during exhaustion show an increase along with a stronger synchronization between the left and right DLPFC (Antal et al., 2022a). When central tiredness brought on by exercise occurs and motor cortical activation declines, fatigue may be compensated in the DLPFC. Accordingly, Lattari et al. (2020) discovered that anodal tDCS applied to the left DLPFC and cathode over the Fp2 at 2 mA for 20 min improved volume load and perceived exertion in comparison to sham tDCS and tDCS employing a reversed montage for lower limb activity in healthy young people (Maldonato et. al., 2018). In comparison to sham stimulation, 20 minutes of anodal tDCS at 2 mA delivered over the left DLPFC (cathode over the Fp2) enhanced the tolerance to the maximal load exercise conducted in the cycloergometer in moderately active women. This study suggests that by preserving the volitional impulse to the motor cortex, altering the neuronal activity in the left DLPFC may improve endurance exercise performance. However, other investigations have not been able to demonstrate any discernible effects of tDCS on exercise performance (Barwood et al., 2016; Monda, Salerno, et al., 2017b; Polito et al., 2020). Recent studies on the improvement of jump performance have confirmed earlier studies on the facilitation of motor learning (Antal et al., 2022b). The possibility of enhancing gross motor power or endurance may be higher compared to the demands of skilled sports, if evidence on experienced musicians could be generalized to sports (Messina et al., 2015; Huang et al., 2009; Polito et al., 2019). An important review, 60% of the studies reported improvement in physical performance when a-tDCS was administered (Angius et al., 2018). More specifically to the type of exercise performed, 62% of the studies involving whole-body exercise reported an improvement in physical, with similar benefits for single-joint exercise (60%). Additionally, 60% studies investigating endurance (both in whole body and single joint exercise) found improvement in performance, while 57% of the studies have found improvement in strength, power, or anaerobic work capacity. However, the effects of tDCS on physical performances are highly variable. Authors suggested that the high inter-individual variability (i.e., responders vs non-responders) to NIBS and more specifically to tDCS could explain the variance in experimental outcomes (López-Alonso et al., 2015). In addition, the different electrode montages used and stimulation protocols could have surely contributed to mixed result. Likewise, due to differences in electrode size and position, as well as to the relatively low focality of induced electric field (Miranda et al., 2013), other brain areas beyond the targeted one could be affected by tDCS and profoundly affect the experimental outcomes. Overall, tDCS seems to improve endurance, strength, power and anaerobic capacity. Taken together, the currently available literature provides interesting insights about the potential for tDCS to enhance physical performance.

NIBS and eating behavior

The first study on non-invasive neuromodulation's use for controlling eating behavior was conducted in 2005 (Uher et al., 2005). The only methods that have been applied in this situation are TMS and tDCS. The targeted region of the brain is the complex DLPFC, which facilitates cognitive control of food intake and is associated with executive processes. The fundamental assumption is that increasing DLPFC activity may change the reward-cognition balance in a way that facilitates cognitive control and may even decrease reward-related systems that cause overeating and food cravings. It is still completely unknown which specific DLPFC -dependent cognitive functions are impacted by rTMS or tDCS and how this influences the reported behavioral effects. Changes in reward valuation mechanisms, attentional biases, or inhibitory control are a few possibilities (Messina et al., 2018; Moscatelli, Sessa, et al., 2021; Valenzano et al., 2019; Val-Laillet et al., 2015; Viggiano et al., 2010). Only the left DLPFC has been the subject of rTMS investigations using excitatory protocols (10 and 20 Hz). Both the right and left DLPFC have been the target of tDCS investigations, however with slightly different approaches/montages. The majority of research have examined the effects on food seeking, perceived hunger, and food intake (all with tDCS, one with rTMS). Overall, they have consistently discovered a severe suppression of appetite and self-reported food cravings on ratings or visual analogue scales (VAS). There is some evidence that the tDCS impact may be more focused on sugar cravings (Esposito et al., 2016; Minervini et al., 2023; Monda, Nigro, et al., 2017).

The findings of these preliminary investigations offer a strong proof of concept for the application of non-invasive neuromodulation to the study of eating behavior (Messina et al., 2018). Potential applications include rebalancing ventral and dorsal brain systems or improving cognitive control and underlying brain regions to support successful weight loss maintenance in obesity (Bonnì et al., 2023; Moscatelli, Messina, et al., 2021; Sperandeo et al., 2018; Val-Laillet et al., 2015; Yao et al., 2023). The general justification for employing noninvasive neuromodulation in the treatment of obesity and eating disorders is pretty evident, but the specifics are still being researched, and the optimum methods and protocols have not yet been established. To produce synergistic results, noninvasive neuromodulation can be utilized alone or in combination with other approaches like behavioral treatment, cognitive training, physical fitness, and diet.

Over the past decade, there is an increasing interest to use brain stimulation as a novel treatment approach for obesity and eating disorders (Ester & Kullmann, 2022). It is evident that multisession studies are more effective to reduce food craving and consumption than single-session approaches (Chen et al., 2020; Song et al., 2019). Moreover, results from various studies suggest that brain stimulation has a positive impact on food craving, particularly for specific foods such as sweets. Most trials were conducted with very limited sample size, which makes it difficult to draw firm conclusions. Yet overall, the literature on tDCS effects on food intake and craving display a mix of positive and null findings. In addition, the exact mechanisms behind tDCS effects remain unclear. Further research should focus on a combination of neuroimaging techniques such as fMRI and tDCS in order to provide underlying mechanisms of anodal and cathodal stimulation. The fast growing literature in brain research elucidated that brain regions do not operate in isolation but interact constantly with each other (Siegel et al., 2015). Multifocal tDCS targeting a whole network increases excitability in the targeted brain area more than twofold over time compared to conventional tDCS (Fischer et al., 2017). Therefore, multifocal tDCS arrangements with smaller electrodes could facilitate to stimulate whole brain networks and thus not only target the DLPFC but indirectly stimulate other brain structures involved in eating behavior regulation (Cotoia et al., 2018).

Discussion

The integration of brain neuromodulation techniques into the realms of sports and nutrition represents a fascinating intersection of science, performance optimization, and human potential. This narrative review explores the multifaceted impact of neuromodulation on athletes' physical abilities, cognitive functions, and nutritional behaviors. One of the most prominent applications of brain neuromodulation in sports is its potential to enhance cognitive functions critical for peak performance (Moscatelli et al., 2023). Techniques such as transcranial direct current stimulation (tDCS) and transcranial magnetic stimulation (TMS) have shown promise in improving attention, decision-making, and memory. These cognitive enhancements can be particularly beneficial for athletes engaged in sports demanding split-second reactions, strategic planning, and complex problem-solving. However, it is essential to note the variability in individual responses and the need for personalized protocols. Athletes seeking cognitive enhancements should approach neuromodulation cautiously, under professional guidance, and with careful consideration of ethical concerns surrounding performance enhancement. Beyond sports performance, neuromodulation also extends its reach into the domain of nutrition. The ability to influence appetite regulation through brain stimulation may aid athletes in managing dietary choices, body weight, and overall nutritional strategies (Ciliberti et al., 2018; Monda et al., 2017). This can have profound implications for athletes who need to balance their energy intake and expenditure for optimal performance. However, the complexities of appetite regulation and the individual variability in responses underscore the need for continued research. Ethical considerations also loom large, especially regarding the potential misuse of neuromodulation for unhealthy dietary practices or body image concerns. The application of brain neuromodulation in sports and nutrition is a dynamic field, marked by promising possibilities and ethical dilemmas. As this technology evolves, regulatory bodies, sports organizations, and practitioners must collaborate to establish guidelines that balance performance enhancement with athlete safety and fairness. Research efforts should continue to elucidate the mechanisms, risks, and benefits associated with neuromodulation techniques in the sporting context.

Conclusion

In these approximately thirty years since the introduction of NIBS techniques, researchers have encountered various technical and theoretical difficulties in defining their optimal use and characterizing the mechanisms induced at a neural level. However, by virtue of the important discoveries and developments that have taken place in recent years, it would seem that the main technical difficulties have been resolved, the methodological bases seem to have been laid and also the operating mechanisms are starting to be clearer. On these bases, interesting scenarios for NIBS begin to be outlined in the clinical, rehabilitation, sport and nutrition fields, with numerous standardized protocols. Surely there is still a long way to go before we arrive at a complete sharing of theoretical models and standardized applications; however, the knowledge attained to date will provide an important background to inspire major advances in this scientific area.

Conflict of interest

The authors have any conflicts of interest to declare.

References

Forbes, S. C., Cordingley, D. M., Cornish, S. M., Gualano, B., Roschel, H., Ostojic, S. M., Rawson, E. S., Roy, B. D., Prokopidis, K., Giannos, P., & Candow, D. G. (2022). Effects of Creatine Supplementation on Brain Function and Health. *Nutrients, 14*(5). https://doi.org/10.3390/nu14050921

Shaw, K. A., Zello, G. A., Rodgers, C. D., Warkentin, T. D., Baerwald, A. R., & Chilibeck, P. D. (2022). Benefits of a plant-based diet and considerations for the athlete. *European Journal of Applied Physiology, 122*(5), 1163–1178. https://doi.org/10.1007/s00421-022-04902-w

Antal, A., Luber, B., Brem, A.-K., Bikson, M., Brunoni, A. R., Cohen Kadosh, R., Dubljević, V., Fecteau, S., Ferreri, F., Flöel, A., Hallett, M., Hamilton, R. H., Herrmann, C. S., Lavidor, M., Loo, C., Lustenberger, C., Machado, S., Miniussi, C., Moliadze, V., … Paulus, W. (2022a). Non-invasive brain stimulation and neuroenhancement. *Clinical Neurophysiology Practice,* 7, 146–165. https://doi.org/10.1016/j.cnp.2022.05.002

Van Ophoven, A. (2023). [Therapeutic value of neuromodulation in women]. *Urologie (Heidelberg, Germany), 62*(2), 153–164. https://doi.org/10.1007/s00120-022-02018-9

Kesikburun, S. (2022). Non-invasive brain stimulation in rehabilitation. *Turkish Journal of Physical Medicine and Rehabilitation, 68*(1), 1–8. https://doi.org/10.5606/tftrd.2022.10608

Barwood, M. J., Butterworth, J., Goodall, S., House, J. R., Laws, R., Nowicky, A., & Corbett, J. (2016). The Effects of Direct Current Stimulation on Exercise Performance, Pacing and Perception in Temperate and Hot Environments. *Brain Stimulation, 9*(6), 842–849. https://doi.org/10.1016/j.brs.2016.07.006

Dumel, G., Bourassa, M.-È., Charlebois-Plante, C., Desjardins, M., Doyon, J., Saint-Amour, D., & De Beaumont, L. (2018). Multisession anodal transcranial direct current stimulation induces motor cortex plasticity enhancement and motor learning generalization in an aging population. *Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology, 129*(2), 494–502. https://doi.org/10.1016/j.clinph.2017.10.041

Edwards, D. J., Cortes, M., Wortman-Jutt, S., Putrino, D., Bikson, M., Thickbroom, G., & Pascual-Leone, A. (2017). Transcranial Direct Current Stimulation and Sports Performance. *Frontiers in Human Neuroscience,* 11, 243. https://doi.org/10.3389/fnhum.2017.00243

Hazime, F. A., da Cunha, R. A., Soliaman, R. R., Romancini, A. C. B., Pochini, A. de C., Ejnisman, B., & Baptista, A. F. (2017). Anodal Transcranial Direct Current Stimulation (Tdcs) Increases Isometric Strength Of Shoulder Rotators Muscles In Handball Players. *International Journal of Sports Physical Therapy, 12*(3), 402–407.

Lattari, E., de Oliveira, B. S., Oliveira, B. R. R., de Mello Pedreiro, R. C., Machado, S., & Neto, G. A. M. (2018). Effects of transcranial direct current stimulation on time limit and ratings of perceived exertion in physically active women. *Neuroscience Letters,* 662, 12–16. https://doi.org/10.1016/j.neulet.2017.10.007

Wang, L., Wang, C., Yang, H., Shao, Q., Niu, W., Yang, Y., & Zheng, F. (2022). Halo Sport Transcranial Direct Current Stimulation Improved Muscular Endurance Performance and Neuromuscular Efficiency During an Isometric Submaximal Fatiguing Elbow Flexion Task. *Frontiers in Human Neuroscience,* 16, 758891. https://doi.org/10.3389/fnhum.2022.758891

Amassian, V. E., Quirk, G. J., & Stewart, M. (1990). A comparison of corticospinal activation by magnetic coil and electrical stimulation of monkey motor cortex. *Electroencephalography and Clinical Neurophysiology, 77*(5), 390–401. https://doi.org/10.1016/0168-5597(90)90061-h

Matsumoto, H., Hanajima, R., Terao, Y., & Ugawa, Y. (2013). Magnetic-motor-root stimulation: review. *Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology, 124*(6), 1055–1067. https://doi.org/10.1016/j.clinph.2012.12.049

Groppa, S., Oliviero, A., Eisen, A., Quartarone, A., Cohen, L. G., Mall, V., Kaelin-Lang, A., Mima, T., Rossi, S., Thickbroom, G. W., Rossini, P. M., Ziemann, U., Valls-Solé, J., & Siebner, H. R. (2012). A practical guide to diagnostic transcranial magnetic stimulation: Report of an IFCN committee. *Clinical Neurophysiology, 123*(5), 858–882. https://doi.org/10.1016/j.clinph.2012.01.010

Vidal-Dourado, M., Conforto, A. B., Caboclo, L. O. S. F., Scaff, M., Guilhoto, L. M. de F. F., & Yacubian, E. M. T. (2014). Magnetic Fields in Noninvasive Brain Stimulation. *The Neuroscientist, 20*(2), 112–121. https://doi.org/10.1177/1073858413491145

Woods, A. J., Antal, A., Bikson, M., Boggio, P. S., Brunoni, A. R., Celnik, P., Cohen, L. G., Fregni, F., Herrmann, C. S., Kappenman, E. S., Knotkova, H., Liebetanz, D., Miniussi, C., Miranda, P. C., Paulus, W., Priori, A., Reato, D., Stagg, C., Wenderoth, N., & Nitsche, M. A. (2016). A technical guide to tDCS, and related non-invasive brain stimulation tools. *Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology, 127*(2), 1031–1048. https://doi.org/10.1016/j.clinph.2015.11.012

Simonsmeier, B. A., Grabner, R. H., Hein, J., Krenz, U., & Schneider, M. (2018). Electrical brain stimulation (tES) improves learning more than performance: A meta-analysis. *Neuroscience and Biobehavioral Reviews,* 84, 171–181. https://doi.org/10.1016/j.neubiorev.2017.11.001

Wagner, T., Valero-Cabre, A., & Pascual-Leone, A. (2007). Noninvasive Human Brain Stimulation. *Annual Review of Biomedical Engineering, 9*(1), 527–565. https://doi.org/10.1146/annurev.bioeng.9.061206.133100

Fregni, F., & Pascual-Leone, A. (2007). Technology Insight: noninvasive brain stimulation in neurology—perspectives on the therapeutic potential of rTMS and tDCS. *Nature Clinical Practice Neurology, 3*(7), 383–393. https://doi.org/10.1038/ncpneuro0530

Rossi, S., Antal, A., Bestmann, S., Bikson, M., Brewer, C., Brockmöller, J., Carpenter, L. L., Cincotta, M., Chen, R., Daskalakis, J. D., Di Lazzaro, V., Fox, M. D., George, M. S., Gilbert, D., Kimiskidis, V. K., Koch, G., Ilmoniemi, R. J., Lefaucheur, J. P., Leocani, L., … Hallett, M. (2021a). Safety and recommendations for TMS use in healthy subjects and patient populations, with updates on training, ethical and regulatory issues: Expert Guidelines. *Clinical Neurophysiology, 132*(1), 269–306. https://doi.org/10.1016/j.clinph.2020.10.003

George, M. S., Nahas, Z., Kozel, F. A., Li, X., Denslow, S., Yamanaka, K., Mishory, A., Foust, M. J., & Bohning, D. E. (2002). Mechanisms and State of the Art of Transcranial Magnetic Stimulation. T*he Journal of ECT, 18*(4), 170–181. https://doi.org/10.1097/00124509-200212000-00002

Rossi, S., Antal, A., Bestmann, S., Bikson, M., Brewer, C., Brockmöller, J., Carpenter, L. L., Cincotta, M., Chen, R., Daskalakis, J. D., Di Lazzaro, V., Fox, M. D., George, M. S., Gilbert, D., Kimiskidis, V. K., Koch, G., Ilmoniemi, R. J., Lefaucheur, J. P., Leocani, L., … Hallett, M. (2021b). Safety and recommendations for TMS use in healthy subjects and patient populations, with updates on training, ethical and regulatory issues: Expert Guidelines. *Clinical Neurophysiology, 132*(1), 269–306. https://doi.org/10.1016/j.clinph.2020.10.003

Zhang, Z., Zheng, S., Yao, Z., Xu, D., Krein, P. T., & Ma, H. (2022). A Coil Positioning Method Integrated With an Orthogonal Decoupled Transformer for Inductive Power Transfer Systems. IEEE *Transactions on Power Electronics, 37*(8), 9983–9998. https://doi.org/10.1109/TPEL.2022.3155270

de Goede, A. A., ter Braack, E. M., & van Putten, M. J. A. M. (2018). Accurate Coil Positioning is Important for Single and Paired Pulse TMS on the Subject Level. *Brain Topography, 31*(6), 917–930. https://doi.org/10.1007/s10548-018-0655-6

Rossini, P. M., Burke, D., Chen, R., Cohen, L. G., Daskalakis, Z., Di, I. R., Di V, L., Ferreri, F., Fitzgerald, P. B., George, M. S., Hallett, M., Lefaucheur, J. P., Langguth, B., Matsumoto, H., Miniussi, C., Nitsche, M. A., Pascual-Leone, A., Paulus, W., Rossi, S., … Ziemann, U. (2015). Non-invasive electrical and magnetic stimulation of the brain, spinal cord, roots and peripheral nerves: Basic principles and procedures for routine clinical and research application. An updated report from an I.F.C.N. Committee 3. *Clin.Neurophysiol.,* 1872-8952 (Electronic).

Fiorenzo Moscatelli, Anna Valenzano, Vincenzo Monda, Maria Ruberto, Giuseppe Monda, A., I.Triggiani, Emanuele Monda, Sergio Chieffi, Ines Villano, Lucia Parisi, Michele Roccella, A., & Messina. (2017). Transcranial magnetic stimulation (tms) application in sport medicine: a brief review. *Acta Medica Mediterranea, 33*(423), 423–430. https://doi.org/10.19193/0393-6384_2017_3_062

Jameson, L. C. (2023). *Transcranial Motor-Evoked Potentials. In Koht, Sloan, Toleikis's Monitoring the Nervous System for Anesthesiologists and Other Health Care Professionals* (pp. 21–34). Springer International Publishing. https://doi.org/10.1007/978-3-031-09719-5_2

Rossi, S., Cappa, S. F., Babiloni, C., Pasqualetti, P., Miniussi, C., Carducci, F., Babiloni, F., & Rossini, P. M. (2001). Prefrontal [correction of Prefontal] cortex in long-term memory: an "interference" approach using magnetic stimulation. *Nature Neuroscience,* 4, 948–952. https://doi.org/10.1038/nn0901-948

Veniero, D., Bortoletto, M., & Miniussi, C. (2012). Cortical modulation of short-latency TMS-evoked potentials. *Frontiers in Human Neuroscience,* 6(January), 352. https://doi.org/10.3389/fnhum.2012.00352

Moscatelli, F., Messina, G., Valenzano, A., Triggiani, A. I., Sessa, F., Carotenuto, M., Tartaglia, N., Ambrosi, A., Cibelli, G., & Monda, V. (2020). 'Effects of twelve weeks' aerobic training on motor cortex excitability. *Journal of Sports Medicine and Physical Fitness.* https://doi.org/10.23736/S0022-4707.20.10677-7

Moscatelli, F., Messina, G., Valenzano, A., Petito, A., Triggiani, A. I., Messina, A., Monda, V., Viggiano, A., De Luca, V., Capranica, L., Monda, M., & Cibelli, G. (2016). Differences in corticospinal system activity and reaction response between karate athletes and non-athletes. *Neurological Sciences: Official Journal of the Italian Neurological Society and of the Italian Society of Clinical Neurophysiology, 37*(12), 1947–1953. https://doi.org/10.1007/s10072-016-2693-8

Moscatelli, F., Messina, G., Valenzano, A., Monda, V., Viggiano, A., Messina, A., Petito, A., Triggiani, A. I., Ciliberti, M. A. P., Monda, M., Capranica, L., & Cibelli, G. (2016). Correction: Functional Assessment of Corticospinal System Excitability in Karate Athletes. *PloS One, 11*(7), e0159846. https://doi.org/10.1371/journal.pone.0159846

Moscatelli, F., Messina, G., Valenzano, A., Monda, V., Viggiano, A., Messina, A., Petito, A., Triggiani, A. I., Ciliberti, M. A. P., Monda, M., Capranica, L., & Cibelli, G. (2016). Functional Assessment of Corticospinal System Excitability in Karate Athletes. *PloS One, 11*(5), e0155998. https://doi.org/10.1371/journal.pone.0155998

Moscatelli, F., Toto, G. A., Valenzano, A., Cibelli, G., Monda, V., Limone, P., Mancini, N., Messina, A., Marsala, G., Messina, G., & Polito, R. (2023). High frequencies (HF) repetitive transcranial magnetic stimulation (rTMS) increase motor coordination performances in volleyball players. *BMC Neuroscience, 24*(1), 30. https://doi.org/10.1186/s12868-023-00796-2

Antal, A., Luber, B., Brem, A.-K., Bikson, M., Brunoni, A. R., Cohen Kadosh, R., Dubljević, V., Fecteau, S., Ferreri, F., Flöel, A., Hallett, M., Hamilton, R. H., Herrmann, C. S., Lavidor, M., Loo, C., Lustenberger, C., Machado, S., Miniussi, C., Moliadze, V., … Paulus, W. (2022b). Non-invasive brain stimulation and neuroenhancement. *Clinical Neurophysiology Practice,* 7, 146–165. https://doi.org/10.1016/j.cnp.2022.05.002

Bortoletto, M., Zazio, A., Bonzano, L., Barchiesi, G., Ferrari, C., Pedullà, L., Gasparotti, R., Miniussi, C., & Bove, M. (2021). Measuring the timing of functional connections through TMS-evoked potentials. *Brain Stimulation, 14*(6), 1712. https://doi.org/10.1016/j.brs.2021.10.408

Lefaucheur, J.-P., Aleman, A., Baeken, C., Benninger, D. H., Brunelin, J., Di Lazzaro, V., Filipović, S. R., Grefkes, C., Hasan, A., Hummel, F. C., Jääskeläinen, S. K., Langguth, B., Leocani, L., Londero, A., Nardone, R., Nguyen, J.-P., Nyffeler, T., Oliveira-Maia, A. J., Oliviero, A., … Ziemann, U. (2020). Evidence-based guidelines on the therapeutic use of repetitive transcranial magnetic stimulation (rTMS): An update (2014-2018). *Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology, 131*(2), 474–528. https://doi.org/10.1016/j.clinph.2019.11.002

Jannati, A., Oberman, L. M., Rotenberg, A., & Pascual-Leone, A. (2023). Assessing the mechanisms of brain plasticity by transcranial magnetic stimulation. *Neuropsychopharmacology: Official Publication of the American College of Neuropsychopharmacology, 48*(1), 191–208. https://doi.org/10.1038/s41386-022-01453-8

Lefaucheur, J.-P., André-Obadia, N., Antal, A., Ayache, S. S., Baeken, C., Benninger, D. H., Cantello, R. M., Cincotta, M., de Carvalho, M., De Ridder, D., Devanne, H., Di Lazzaro, V., Filipović, S. R., Hummel, F. C., Jääskeläinen, S. K., Kimiskidis, V. K., Koch, G., Langguth, B., Nyffeler, T., … Garcia-Larrea, L. (2014). Evidence-based guidelines on the therapeutic use of repetitive transcranial magnetic stimulation (rTMS). *Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology, 125*(11), 2150–2206. https://doi.org/10.1016/j.clinph.2014.05.021

Perinelli, A., Tabarelli, D., Miniussi, C., & Ricci, L. (2019). Dependence of connectivity on geometric distance in brain networks. *Scientific Reports, 9*(1), 13412. https://doi.org/10.1038/s41598-019-50106-2

Savino, R., Polito, A. N., Bellomo, A., Moscatelli, F., Polito, R., Valenzano, A. A., Messina, G., Cibelli, G., & Ventriglio, A. (2023). Transcranial magnetic stimulation as a new therapeutical approach in autism spectrum disorders and attention deficit hyperactivity disorder – a review. *European Journal of Clinical and Experimental Medicine, 21*(1), 133–144. https://doi.org/10.15584/ejcem.2023.1.17

Machado, S., Jansen, P., Almeida, V., & Veldema, J. (2019). Is tDCS an Adjunct Ergogenic Resource for Improving Muscular Strength and Endurance Performance? A Systematic Review. *Frontiers in Psychology,* 10, 1127. https://doi.org/10.3389/fpsyg.2019.01127

Bastani, A., & Jaberzadeh, S. (2012). Does anodal transcranial direct current stimulation enhance excitability of the motor cortex and motor function in healthy individuals and subjects with stroke: a systematic review and meta-analysis. *Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology, 123*(4), 644–657. https://doi.org/10.1016/j.clinph.2011.08.029

Park, S.-B., Sung, D. J., Kim, B., Kim, S., & Han, J.-K. (2019). Transcranial Direct Current Stimulation of motor cortex enhances running performance. *PloS One, 14*(2), e0211902. https://doi.org/10.1371/journal.pone.0211902

Amanda S Morrison, Andero Uusberg, J. R. (2022). Assessing and improving public mental health literacy concerning rTMS. *BMC Neuroscience,* 1. https://doi.org/10.1186/s12888-022-03880-9

Gornerova, N., Brunovsky, M., Klirova, M., Novak, T., Zaytseva, Y., Koprivova, J., Bravermanova, A., & Horacek, J. (2023). The effect of low-frequency rTMS on auditory hallucinations, EEG source localization and functional connectivity in schizophrenia. *Neuroscience Letters,* 794, 136977. https://doi.org/10.1016/j.neulet.2022.136977

Cabral, M. E., Baltar, A., Borba, R., Galvão, S., Santos, L., Fregni, F., & Monte-Silva, K. (2015). Transcranial direct current stimulation. *NeuroReport, 26*(11), 618–622. https://doi.org/10.1097/WNR.0000000000000397

Lattari, E., Andrade, M. L., Filho, A. S., Moura, A. M., Neto, G. M., Silva, J. G., Rocha, N. B., Yuan, T.-F., Arias-Carrión, O., & Machado, S. (2016). Can Transcranial Direct Current Stimulation Improve the Resistance Strength and Decrease the Rating Perceived Scale in Recreational Weight-Training Experience? *Journal of Strength and Conditioning Research, 30*(12), 3381–3387. https://doi.org/10.1519/JSC.0000000000001457

Lattari, E., Rosa Filho, B. J., Fonseca Junior, S. J., Murillo-Rodriguez, E., Rocha, N., Machado, S., & Maranhão Neto, G. A. (2020). Effects on Volume Load and Ratings of Perceived Exertion in Individuals' Advanced Weight Training After Transcranial Direct Current Stimulation. *Journal of Strength and Conditioning Research, 34*(1), 89–96. https://doi.org/10.1519/JSC.0000000000002434

Al-Tawarah, N. M., Kaptan, Z., Abu-Harirah, H. A., Nofal, M., Almajali, B., Jarrar, S., Bayraktaroğlu, Z., Qaralleh, H., Khleifat, K. M., Ziylan, Z. Y., Al Dmour, R. H., Alqaraleh, M., & Karamursel, S. (2022). Effectiveness of Anodal otDCS Following with Anodal tDCS Rather than tDCS Alone for Increasing of Relative Power of Intrinsic Matched EEG Bands in Rat Brains. *Brain Sciences, 13*(1). https://doi.org/10.3390/brainsci13010072

Goodall, S., Howatson, G., Romer, L., & Ross, E. (2014). Transcranial magnetic stimulation in sport science: A commentary. *European Journal of Sport Science,* 14 Suppl 1(February 2013), S332-40. https://doi.org/10.1080/17461391.2012.704079

Karlinsky, A., Zentgraf, K., & Hodges, N. J. (2017). Action-skilled observation: Issues for the study of sport expertise and the brain. *Progress in Brain Research,* 234, 263–289. https://doi.org/10.1016/bs.pbr.2017.08.009

Monda, V., Salerno, M., Fiorenzo, M., Villano, I., Viggiano, A., Sessa, F., Triggiani, A. I., Cibelli, G., Valenzano, A., Marsala, G., Zammit, C., Ruberto, M., Messina, G., Monda, M., Luca, V. D., & Messina, A. (2017a). Role of sex hormones in the control of vegetative and metabolic functions of middle-aged women. *Frontiers in Physiology, 8*(OCT). https://doi.org/10.3389/fphys.2017.00773

Maldonato, M.N, Sperandeo, , Dell'Orco, S, Iennaco, D, Cerroni, F, Romano, P, Salerno, M, Maltese, A, Roccella, M, Parisi, L, Tripi, G, Moscatelli, F, Sessa, F, monica, S, Cibelli, G, Messina, G, Monda, M, Chieffi, S, Villano, I, Monda, V, Messina, A, Rub, A. (2018). Mind, brain and altered states of consciousness. *Acta Medica Mediterranea, 34*(2), 357–366. https://doi.org/10.19193/0393-6384_2018_2_56

Monda, V., Salerno, M., Fiorenzo, M., Villano, I., Viggiano, A., Sessa, F., Triggiani, A. I., Cibelli, G., Valenzano, A., Marsala, G., Zammit, C., Ruberto, M., Messina, G., Monda, M., Luca, V. D., & Messina, A. (2017b). Role of sex hormones in the control of vegetative and metabolic functions of middle-aged women. *Frontiers in Physiology, 8*(OCT). https://doi.org/10.3389/fphys.2017.00773

Polito, R., Monda, V., Nigro, E., Messina, A., Di Maio, G., Giuliano, M. T., Orrù, S., Imperlini, E., Calcagno, G., Mosca, L., Mollica, M. P., Trinchese, G., Scarinci, A., Sessa, F., Salerno, M., Marsala, G., Buono, P., Mancini, A., Monda, M., … Messina, G. (2020). The Important Role of Adiponectin and Orexin-A, Two Key Proteins Improving Healthy Status: Focus on Physical Activity. *Frontiers in Physiology,* 11. https://doi.org/10.3389/fphys.2020.00356

Giovanni Messina, Anna AValenzano, Fiorenzo Moscatelli, Antonio I Triggiani, Laura Capranica, Antonietta Messina, L. P., & Domenico Tafuri, G. C. and M. M. (2015). Effects of Emotional Stress on Neuroendocrine and Autonomic Functions in Skydiving. *Journal of Psychiatry, 18*(4), 1–7. https://doi.org/10.4172/2378-5756.1000280

Huang, Y.-Z., Sommer, M., Thickbroom, G., Hamada, M., Pascual-Leonne, A., Paulus, W., Classen, J., Peterchev, A. V, Zangen, A., & Ugawa, Y. (2009). Consensus: New methodologies for brain stimulation. *Brain Stimulation, 2*(1), 2–13. https://doi.org/10.1016/j.brs.2008.09.007

Polito, R., Nigro, E., Elce, A., Monaco, M. L., Iacotucci, P., Carnovale, V., Comegna, M., Gelzo, M., Zarrilli, F., Corso, G., Castaldo, G., & Daniele, A. (2019). Adiponectin Expression Is Modulated by Long-Term Physical Activity in Adult Patients Affected by Cystic Fibrosis. *Mediators of Inflammation,* 2019, 2153934. https://doi.org/10.1155/2019/2153934

Angius, L., Pascual-Leone, A., & Santarnecchi, E. (2018). Brain stimulation and physical performance. *Progress in Brain Research,* 240, 317–339. https://doi.org/10.1016/bs.pbr.2018.07.010

López-Alonso, V., Fernández-del-Olmo, M., Costantini, A., Gonzalez-Henriquez, J. J., & Cheeran, B. (2015).

Intra-individual variability in the response to anodal transcranial direct current stimulation. *Clinical Neurophysiology, 126*(12), 2342–2347. https://doi.org/10.1016/j.clinph.2015.03.022

Miranda, P. C., Mekonnen, A., Salvador, R., & Ruffini, G. (2013). The electric field in the cortex during transcranial current stimulation. *NeuroImage,* 70, 48–58. https://doi.org/10.1016/j.neuroimage.2012.12.034

Uher, R., Yoganathan, D., Mogg, A., Eranti, S. V, Treasure, J., Campbell, I. C., McLoughlin, D. M., & Schmidt, U. (2005). Effect of left prefrontal repetitive transcranial magnetic stimulation on food craving. *Biological Psychiatry, 58*(10), 840–842. https://doi.org/10.1016/j.biopsych.2005.05.043

Messina, A., Monda, M., Valenzano, A., Messina, G., Villano, I., Moscatelli, F., Cibelli, G., Marsala, G., Polito, R., Ruberto, M., Carotenuto, M., Monda, V., Viggiano, A., Daniele, A., & Nigro, E. (2018). Functional changes induced by orexin a and adiponectin on the sympathetic/parasympathetic balance. *Frontiers in Physiology.* https://doi.org/10.3389/fphys.2018.00259

Moscatelli, F., Sessa, F., Valenzano, A., Polito, R., Monda, V., Cibelli, G., Villano, I., Pisanelli, D., Perrella, M., Daniele, A., Monda, M., Messina, G., & Messina, A. (2021). Covid-19: Role of nutrition and supplementation. *In Nutrients.* https://doi.org/10.3390/nu13030976

Valenzano, A., Polito, R., Trimigno, V., Di Palma, A., Moscatelli, F., Corso, G., Sessa, F., Salerno, M., Montana, A., Di Nunno, N., Astuto, M., Daniele, A., Carotenuto, M., Messina, G., Cibelli, G., & Monda, V. (2019). Effects of very low calorie ketogenic diet on the orexinergic system, visceral adipose tissue, and ROS production. *Antioxidants.* https://doi.org/10.3390/antiox8120643

Val-Laillet, D., Aarts, E., Weber, B., Ferrari, M., Quaresima, V., Stoeckel, L. E., Alonso-Alonso, M., Audette, M., Malbert, C. H., & Stice, E. (2015). Neuroimaging and neuromodulation approaches to study eating behavior and prevent and treat eating disorders and obesity. *NeuroImage. Clinical,* 8, 1–31. https://doi.org/10.1016/j.nicl.2015.03.016

Viggiano, A., Nicodemo, U., Viggiano, E., Messina, G., Viggiano, A., Monda, M., & De Luca, B. (2010). Mastication overload causes an increase in O2− production into the subnucleus oralis of the spinal trigeminal nucleus. *Neuroscience, 166*(2), 416–421. https://doi.org/10.1016/j.neuroscience.2009.12.071

Esposito, T., Lobaccaro, J. M., Esposito, M. G., Monda, V., Messina, A., Paolisso, G., Varriale, B., Monda, M., & Messina, G. (2016). Effects of low-carbohydrate diet therapy in overweight subjects with autoimmune thyroiditis: possible synergism with ChREBP. *Drug Design, Development and Therapy,* 10, 2939–2946. https://doi.org/10.2147/DDDT.S106440

Minervini, A., LaVarco, A., Zorns, S., Propper, R., Suriano, C., & Keenan, J. P. (2023). Excitatory Dorsal Lateral Prefrontal Cortex Transcranial Magnetic Stimulation Increases Social Anxiety. *Brain Sciences, 13*(7), 989. https://doi.org/10.3390/brainsci13070989

Monda, V., Nigro, E., Ruberto, M., Monda, G., Valenzano, A., Triggiani, A. I., Moscatelli, F., Monda, E., Villano, I., Roccella, M., Parisi, L., & Messina, A. (2017). Synergism or competition between zinc and chromium dietary levels on insulin action mechanism. A method to investigate. *Acta Medica Mediterranea.* https://doi.org/10.19193/0393-6384_2017_4_085

Bonnì, S., Borghi, I., Maiella, M., Casula, E. P., Koch, G., Caltagirone, C., & Gainotti, G. (2023). Transcranial Direct Current Stimulation Effects on the Neural Substrate of Conceptual Representations. *Brain Sciences, 13*(7), 1037. https://doi.org/10.3390/brainsci13071037

Moscatelli, F., Messina, A., Valenzano, A., Monda, V., Salerno, M., Sessa, F., Torre, E. La, Tafuri, D., Scarinci, A., Perrella, M., Marsala, G., Monda, M., Cibelli, G., Porro, C., & Messina, G. (2021). Transcranial magnetic stimulation as a tool to investigate motor cortex excitability in sport. *In Brain Sciences.* https://doi.org/10.3390/brainsci11040432

Sperandeo, R., Maldonato, M. N., Messina, A., Cozzolino, P., Monda, M., Cerroni, F., Romano, P., Salerno, M., Maltese, A., Roccella, M., Parisi, L., Tripi, G., Moscatelli, F., Sessa, F., Salerno, M., Cibelli, G., Messina, G., Monda, V., Chieffi, S., … Valenzano, A. (2018). Orexin system: Network multi-tasking. *Acta Medica Mediterranea, 34*(2), 349–356. https://doi.org/10.19193/0393-6384_2018_2_55

Yao, J., Song, B., Shi, J., Yin, K., & Du, W. (2023). Effects of Repetitive Transcranial Magnetic Stimulation at the Cerebellum on Working Memory. *Brain Sciences, 13*(8), 1158. https://doi.org/10.3390/brainsci13081158

Ester, T., & Kullmann, S. (2022). Neurobiological regulation of eating behavior: Evidence based on non-invasive brain stimulation. *Reviews in Endocrine & Metabolic Disorders, 23*(4), 753–772. https://doi.org/10.1007/s11154-021-09697-3

Chen, J., Qin, J., He, Q., & Zou, Z. (2020). A Meta-Analysis of Transcranial Direct Current Stimulation on Substance and Food Craving: What Effect Do Modulators Have? *Frontiers in Psychiatry,* 11. https://doi.org/10.3389/fpsyt.2020.00598

Song, S., Zilverstand, A., Gui, W., Li, H., & Zhou, X. (2019). Effects of single-session versus multi-session non-invasive brain stimulation on craving and consumption in individuals with drug addiction, eating disorders or obesity: A meta-analysis. *Brain Stimulation, 12*(3), 606–618. https://doi.org/10.1016/j.brs.2018.12.975

Siegel, M., Buschman, T. J., & Miller, E. K. (2015). Cortical information flow during flexible sensorimotor decisions. *Science, 348*(6241), 1352–1355. https://doi.org/10.1126/science.aab0551

Fischer, D. B., Fried, P. J., Ruffini, G., Ripolles, O., Salvador, R., Banus, J., Ketchabaw, W. T., Santarnecchi, E., Pascual-Leone, A., & Fox, M. D. (2017). Multifocal tDCS targeting the resting state motor network increases cortical excitability beyond traditional tDCS targeting unilateral motor cortex. *NeuroImage,* 157, 34–44. https://doi.org/10.1016/j.neuroimage.2017.05.060

Cotoia, A., Dibello, F., Moscatelli, F., Sciusco, A., Polito, P., Modolo, A., Gallo, C., Cibelli, G., & Cinnella, G. (2018). Effects of tibetan music on neuroendocrine and autonomic functions in patients waiting for surgery: A randomized, controlled study. *Anesthesiology Research and Practice.* https://doi.org/10.1155/2018/9683780

Ciliberti, M. A. P., Santoro, F., Di Martino, L. F. M., Rinaldi, A. C., Salvemini, G., Cipriani, F., Triggiani, A. I., Moscatelli, F., Valenzano, A., Di Biase, M., Brunetti, N. D., & Cibelli, G. (2018). Predictive value of very low frequency at spectral analysis among patients with unexplained syncope assessed by head-up tilt testing. *Archives of Cardiovascular Diseases.* https://doi.org/10.1016/j.acvd.2017.04.006

Вплив нейромодуляції головного мозку на заняття спортом та харчування: описовий огляд

П'єрпаоло Лімоне[1AD], Фіоренцо Москателлі[1AD], Алесія Скарінчі[2AD], Марко Каротенуто[3BE], Антонієтта Мессіна[3AD], Марчелліно Монда[3AD], Анна Діпаце[1AD], Марко Ла Марра[3BD], Інес Віллано[1BD], Паола Бассі[3BE], Ріта Політо[4BD], Джованні Мессіна[3AD]

[1]Телематичний університет Пегасо
[2]Телематичний університет Меркаторум
[3]Університет імені Луїджі Ванвітеллі в Кампанії
[4]Університет Фоджа

Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 12 с., 83 джерела.

Мета дослідження. Наприкінці XX століття розробка високонадійних і безболісних неінвазивних методів і пристроїв транскраніальної стимуляції головного мозку викликала значний науковий та клінічний інтерес у багатьох галузях. У нейрології, з моменту впровадження інноваційних та неінвазивних пристроїв, таких як стимулятор мозку, дослідження кортикальних процесів та їх нейронної основи відіграє фундаментальну роль.

Крім того, увагу нейрологів привертає застосування терапевтичних методів для лікування потягу до їжі. Цей описовий огляд має на меті пояснити зростаючий і постійний інтерес до проведення нейрологічних експериментів у сфері неінвазивної транскраніальної стимуляції.

Матеріал та методи. Після вступної частини, що пояснює історичну еволюцію неінвазивної стимуляції головного мозку (NIBS); ми спробуємо надати огляд двох методів стимуляції — транскраніальна магнітна стимуляція та транскраніальна стимуляція постійним струмом (TMS і tDCS); ми опишемо різні типи стимуляції, які можуть бути виконані із застосуванням цих методів, ефекти збудження/пригнічення, а також різні механізми дії на рівні активності головного мозку.

Результати. Ми також надамо деякі пояснення щодо наслідків фасилітативного/інгібіторного ефектів і того, як ці методи стимуляції можуть бути використані для поглиблення знань з нейрофункціональної організації головного мозку.

Висновки. Результати дослідження показали вплив нейромодуляції головного мозку на заняття спортом та харчування.

Ключові слова: неінвазивна стимуляція головного мозку (NIBS), транскраніальна магнітна стимуляція (TMS), транскраніальна стимуляція постійним струмом (tDCS), кортикальне збудження, потяг до їжі.

Information about the authors:

Limone, Pierpaolo: pierpaolo.limone@unipegaso.it; https://orcid.org/0000-0003-3852-4005; Department of Wellbeing, Nutrition and Sport, Pegaso Telematic University, Centro Direzionale Isola F2, 80143 Naples, Italy.

Moscatelli, Fiorenzo: fiorenzo.moscatelli@unipegaso.it; https://orcid.org/0000-0003-1274-0332; Department of Wellbeing, Nutrition and Sport, Pegaso Telematic University, Centro Direzionale Isola F2, 80143 Naples, Italy.

Scarinci, Alessia: alessia.scrinci@unimercatorum.it; https://orcid.org/0000-0002-3174-7137; Mercatorum Telematic University, Piazza Mattei, 10, 00186 Roma, Italy.

Carotenuto, Marco: marco.carotenuto@unicampania.it; https://orcid.org/0000-0002-8136-7597; Department of Mental and Physical Health and Preventive Medicine, University of Campania "Luigi Vanvitelli", Piazza Luigi Miraglia, 2, 80138 Naples, Italy.

Messina, Antonietta: antonietta.messina@unicampania.it; https://orcid.org/0000-0001-8343-432X; Department of Experimental Medicine, Section of Human Physiology and Unit of Dietetics and Sports Medicine, University of Campania "Luigi Vanvitelli", Piazza Luigi Miraglia, 2, 80138 Naples, Italy.

Monda, Marcellino: marcellino.monda@unicampania.it; https://orcid.org/0000-0002-7184-218X; Department of Experimental Medicine, Section of Human Physiology and Unit of Dietetic and Sport Medicine, University of Campania "Luigi Vanvitelli", Piazza Luigi Miraglia, 2, 80138 Naples, Italy.

Dipace, Anna: anna.dipace@unipegaso.it; https://orcid.org/0000-0001-9826-073X; Department of Wellbeing, Nutrition and Sport, Pegaso Telematic University, Centro Direzionale Isola F2, 80143 Naples, Italy.

La Marra, Marco: marco.lamarra@unicampania.it; https://orcid.org/0000-0001-7488-8493; Department of Experimental Medicine, Section of Human Physiology and Unit of Dietetics and Sports Medicine, University of Campania "Luigi Vanvitelli", Piazza Luigi Miraglia, 2, 80138 Naples, Italy.

Villano, Ines: ines.villano@unipegaso.it; https://orcid.org/0000-0002-1755-358X; Department of Wellbeing, Nutrition and Sport, Pegaso Telematic University, Centro Direzionale Isola F2, 80143 Naples, Italy.

Bassi, Paola: paola.bassi@unicampania.it; https://orcid.org/0000-0002-5652-3420; Department of Experimental Medicine, Section of Human Physiology and Unit of Dietetics and Sports Medicine, University of Campania "Luigi Vanvitelli", Piazza Luigi Miraglia, 2, 80138 Naples, Italy.

Polito, Rita: rita.polito@unifg.it; https://orcid.org/0000-0003-1313-2574; Department of Clinical and Experimental Medicine, University of Foggia, Via A. Gramsci 89/91, 71122 Foggia, Italy.

Messina, Giovanni: giovanni.messina@unifg.it; https://orcid.org/0000-0002-0011-867X; Department of Clinical and Experimental Medicine, University of Foggia, Via A. Gramsci 89/91, 71122 Foggia, Italy.

Cite this article as: Limone, P., Moscatelli, F., Scarinci, A., Carotenuto, M., Messina, A., Monda, M., Dipace, A., La Marra, M., Villano, I., Bassi, P., Polito, R., & Messina, G. (2024). Brain Neuromodulation Effects on Sport and Nutrition: A Narrative Review. *Physical Education Theory and Methodology, 24*(1), 136–147. https://doi.org/10.17309/tmfv.2024.1.17

Received: 05.01.2024. Accepted: 08.02.2024. Published: 29.02.2024